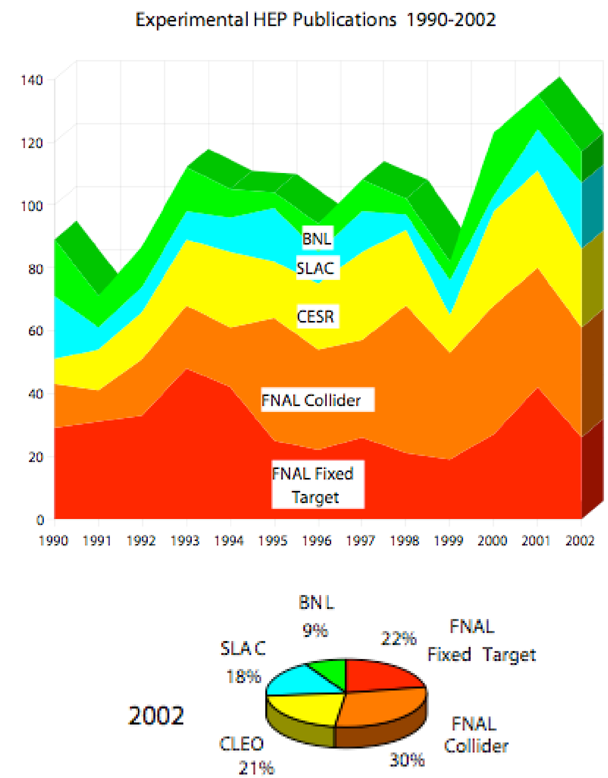
Physics at the Precision Frontier

Recent Physics Results Highlights

KTeV (E832,E799), Hyper-CP,
NuTeV, NUSEA, DONUT,
E791, FOCUS, SELEX, E835

The Precision Physics Frontier

- Easier things have been done already
- Need more statistics and improved experimental techniques and/or specialized facilities/beams
- Precise comparisons or search for rare or forbidden processes



CP and CPT Violation Studies

- CP violation is one of the least tested part of SM
- CP violation plays a role in matter/anti-matter asymmetry
- Any CPT violation would also play a role

K_L semileptonic decay charge asymmetry from KTeV

$$K_L \quad (1+\varepsilon)K^0 - (1-\varepsilon)\overline{K^0}$$

$$K^0 \rightarrow \pi^- e^+ \nu \qquad \overline{K^0} \rightarrow \pi^+ e^- \overline{\nu}$$

$$\delta_L = \frac{B(e^+\pi^-) - B(e^-\pi^+)}{B(e^+\pi^-) + B(e^-\pi^+)} = 2\mathrm{Re}(\varepsilon)$$

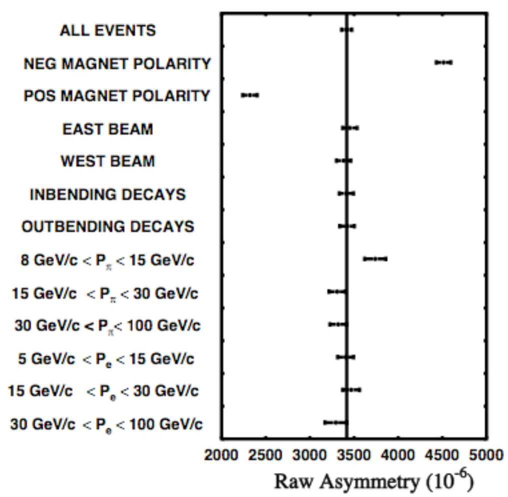
CP violation in mixing

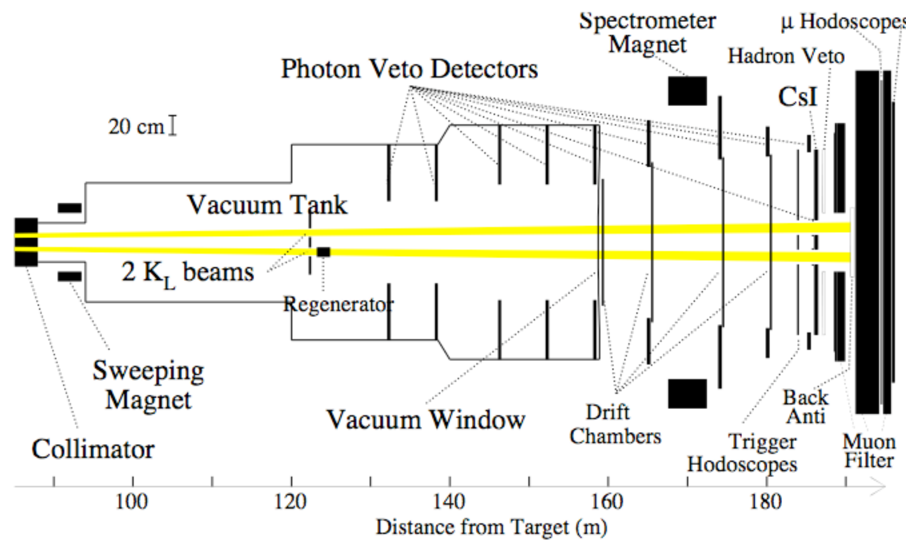
Compare to K→ ππ

$K_L \to \pi e \nu$ Asymmetry in KTeV

$$\text{Raw } \delta_L = \frac{R-1}{R+1}$$

$$R^4 = \frac{B(e^+\pi^-)A(e^+\pi^-,E,+)N(K_L,E,+)}{B(e^-\pi^+)A(e^-\pi^+,E,-)N(K_L,E,-)} \times \frac{B(e^+\pi^-)A(e^+\pi^-,E,-)N(K_L,E,-)}{B(e^-\pi^+)A(e^-\pi^+,E,+)N(K_L,E,+)}$$
$$\times \frac{B(e^+\pi^-)A(e^+\pi^-,W,+)N(K_L,W,+)}{B(e^-\pi^+)A(e^-\pi^+,W,-)N(K_L,W,-)} \times \frac{B(e^+\pi^-)A(e^+\pi^-,W,-)N(K_L,W,-)}{B(e^-\pi^+)A(e^-\pi^+,W,+)N(K_L,W,+)}$$



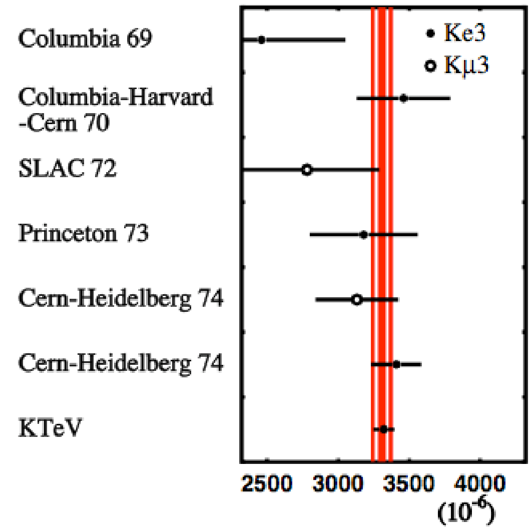


$$\delta_L = [3322 \pm 58(stat.) \pm 47(syst.)] \times 10^{-6}$$

$K_L \to \pi e \nu$ Asymmetry in KTeV

World Ave. $\delta_L = (3.307 \pm 0.063) \times 10^{-3}$

Expect $(3.32 \pm 0.03) \times 10^{-3}$
from $K \to \pi\pi$ with only indirect CP viol.

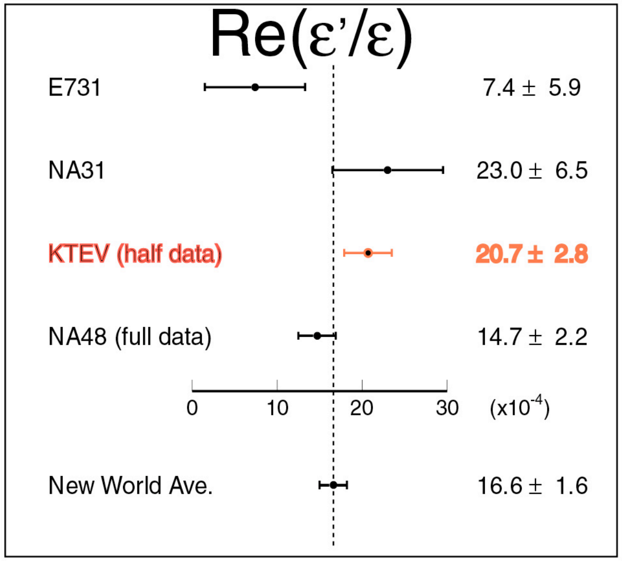


Take out direct CP contribution (ε')
compare quantity that is sensitive to
CPT violation in Ke3 and $K\pi 2$ decays:

$$\text{“}\delta_{K\pi 2} - \delta_{Ke3}\text{”} = \mathrm{Re}\left(\frac{2}{3}\eta_{+-} + \frac{1}{3}\eta_{00}\right) - \frac{\delta_L}{2} = -3 \pm 35\,ppm$$

The World's best CPT limit on $\Delta S = \pm\Delta Q$ transitions

CP and CPT with $K \rightarrow \pi\pi$

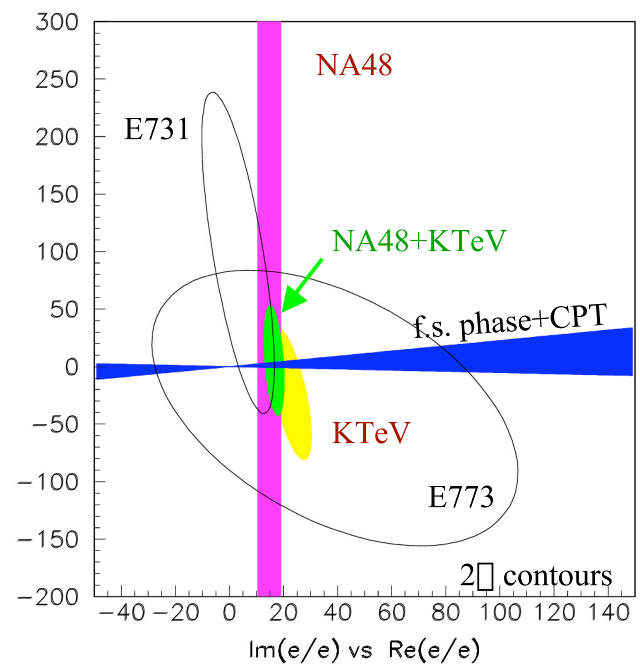


KTeV published result for direct CP violation

World ave. $Re(\varepsilon'/\varepsilon) = (16.6 \pm 1.6) \times 10^{-4}$
(confidence level = 10%)

KTeV has sensitivity to $Im(\varepsilon'/\varepsilon)$ which could show CPT violation:

$$-3Im(\varepsilon'/\varepsilon) \approx \Delta\Phi = \phi_{00} - \phi_{+-}$$
$$= 0.39° \pm 0.22°(\text{stat.}) \pm 0.45°(\text{syst.})$$



CP Violation with HyperCP

Test CP violation everywhere - Related in quarks to CKM δ

$\Xi^- \to \Lambda\pi^-, \bar{\Xi}^0, \Lambda^0 \to \pi^- p$

$$\frac{dn}{d\Omega} = \frac{1}{4\pi}(1 + \alpha P \cos\theta) \quad \alpha = -\bar{\alpha}$$ If CP is conserved

$$A \equiv (\alpha + \bar{\alpha})/(\alpha - \bar{\alpha}) \qquad A_{\Xi\Lambda} = \frac{\alpha_\Xi \alpha_\Lambda - \alpha_{\bar{\Xi}}\alpha_{\bar{\Lambda}}}{\alpha_\Xi \alpha_\Lambda + \alpha_{\bar{\Xi}}\alpha_{\bar{\Lambda}}} \approx A_\Xi + A_\Lambda$$

$A_{\Xi\Lambda} = (-1.5 \pm 5.1(\text{stat.}) \pm 4.8(\text{syst.})) \times 10^{-4}$

From 10% of 1999 data - expect from all data $\delta A_{\Xi\Lambda} = 1.4 \times 10^{-4}$

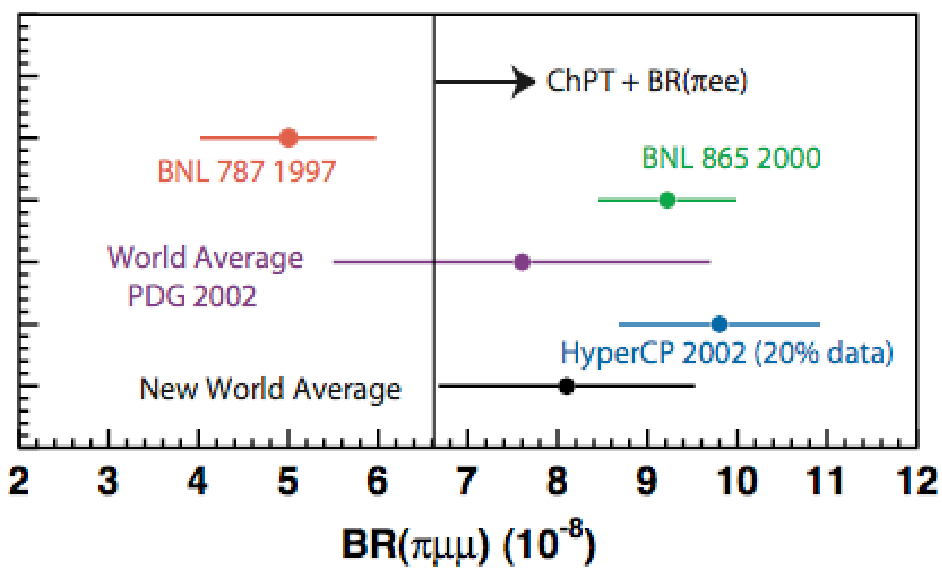
Theory	A_Λ	A_Ξ
Superweak	0	0
CKM (“SM”)	$(-0.6 \text{ to } 6.8) \times 10^{-5}$	$(-0.1 \text{ to } 1) \times 10^{-5}$
2-Higgs	$\approx -2 \times 10^{-5}$	$\approx -3 \times 10^{-4}$
Left-Right	$< \approx 5 \times 10^{-4}$	$< \approx 10^{-4}$
Supersymmetric	$< \approx 1.9 \times 10^{-3}$	$< \approx 10^{-4}$

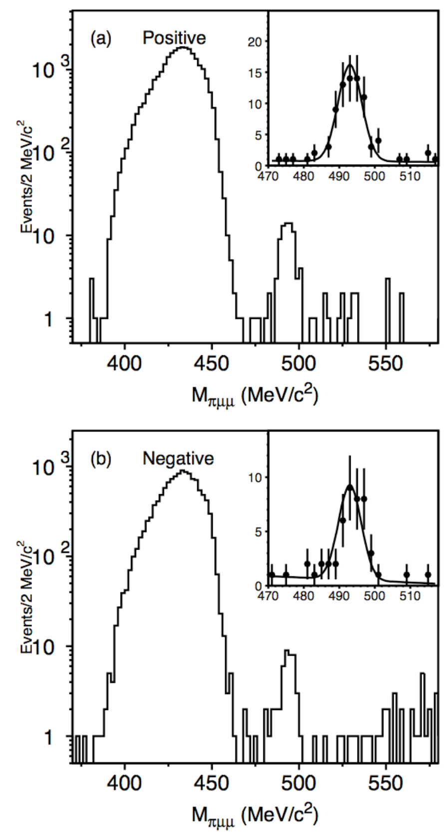
Rare decays with HyperCP

Specialized experiments are actually quite general:

Recently published Flavor changing decay $K^\pm \rightarrow \pi^\pm\mu^+\mu^-$

$$B(K^\pm_{\pi\mu\mu}) = (9.8 \pm 1.0(\mathrm{stat.}) \pm 0.5(\mathrm{syst.})) \times 10^{-8}$$



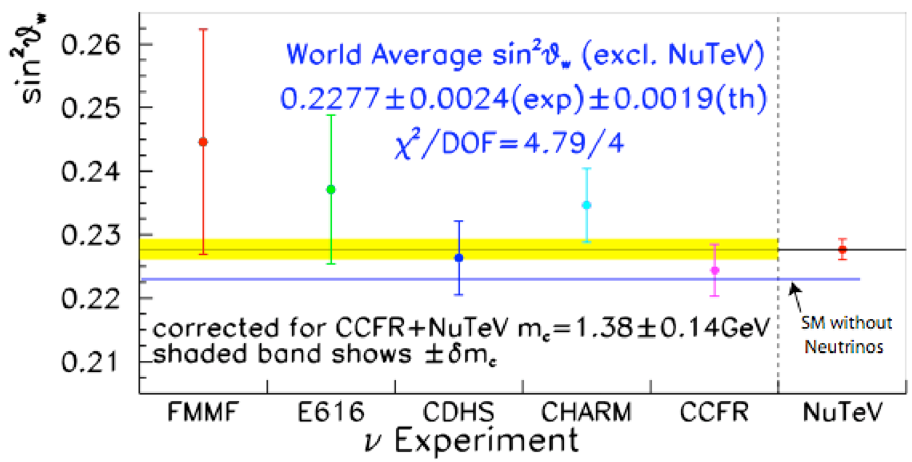


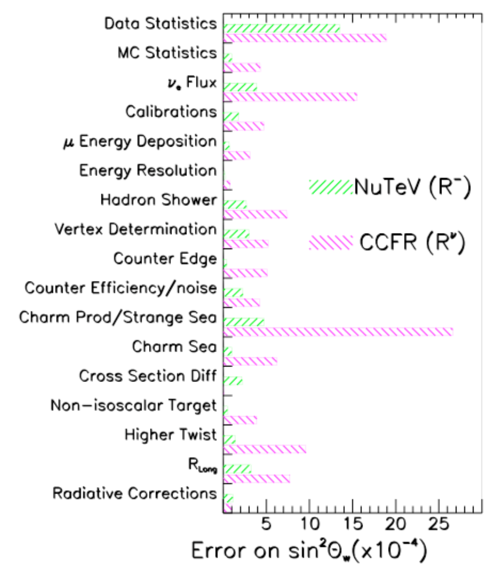
Resolves situation with 20% of data

Electroweak Tests with Neutrinos

Want precise EW tests other than with e^+e^- and at Z-pole

- Sensitive to new physics (e.g. other than Z-exchange)
- Test neutral-current neutrino couplings





Reduce systematic uncertainties by comparing □ with □

Electroweak Tests with NuTeV

Clean ν_μ and $\bar{\nu}_\mu$ beams using a SSQT beam line

- Reduce systematics by comparing ν and $\bar{\nu}$ ("ratio of ratios")
- Reduce systematics by reducing ν_e background

NuTeV sees a difference between neutrinos and antineutrinos compared to the SM:

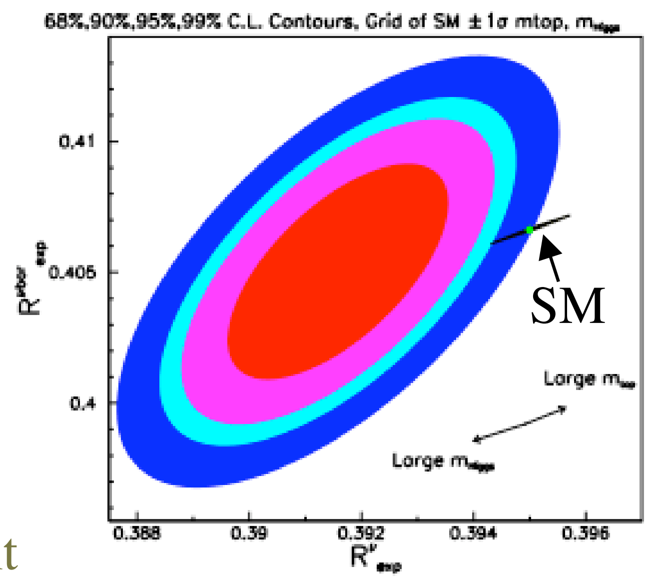
- Due to real difference in interactions between ν and ν-bar

Or/And

- Due to difference in asymmetries in PDFs from QCD (LO vs NLO?)

Knowledge of PDF is crucially important

Need more - e.g. recent NuSea publication

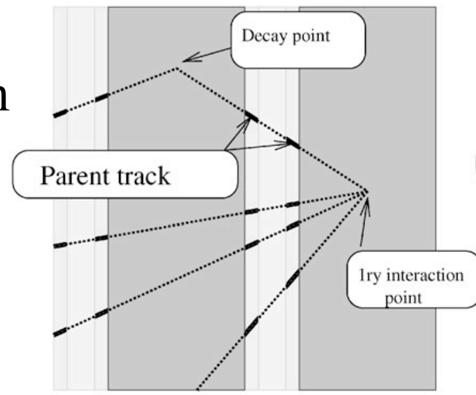


$\sigma(\nu N \to \nu X)/\sigma(\nu N \to l^- X)$

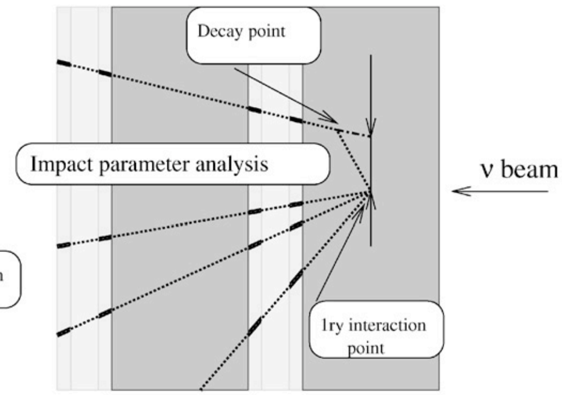
DONUT - a Start on ν_τ Studies?

Study all Neutrinos!

- Direct observation from Phase I - Long decays
- Now working on Phase II - Short decays



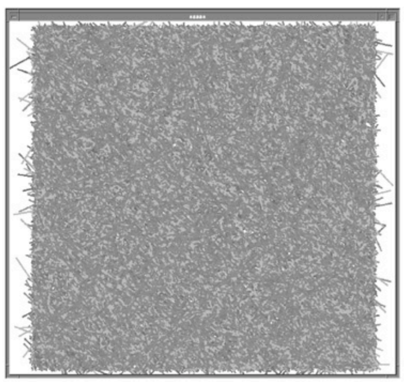
Long Decay



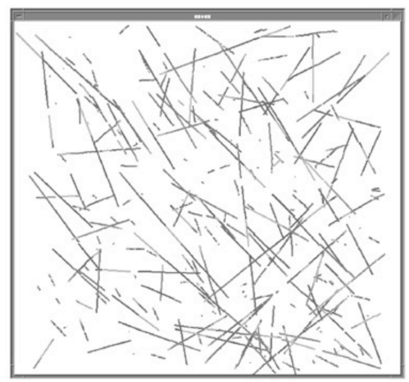
Short Decay

Totally automated scanning:

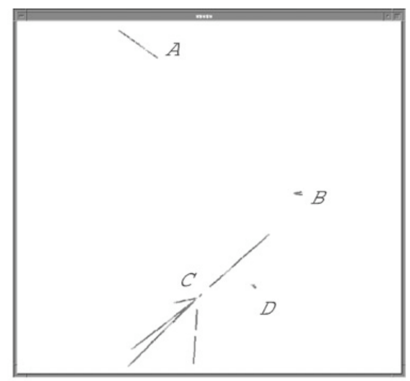
Advances in experimental techniques



Scanned tracks



Non-penetrating and good quality track requirements



Vertex requirements

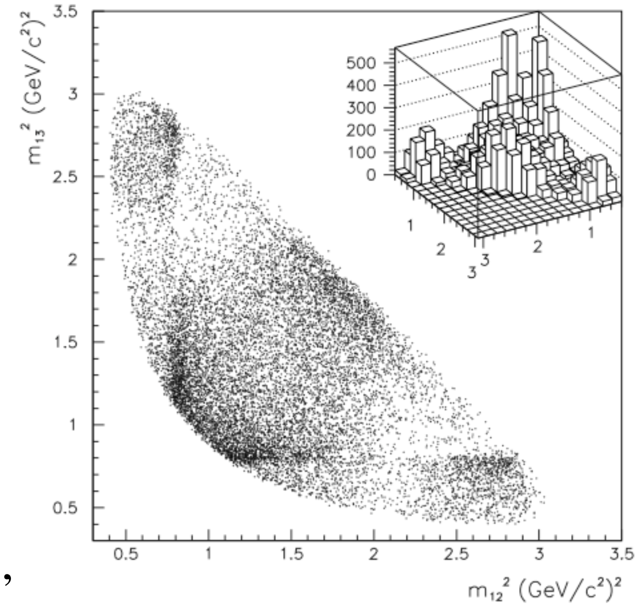
Charm - A Laboratory for Light Quarks

Dalitz Plot analyses provides info on:

- resonant substructure in decays
- role of FSI in decays
- Non-spectator contributions

With higher statistics also provides:

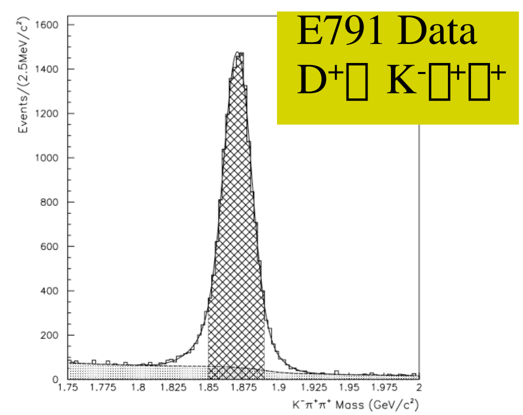
- study of light quark spectroscopy in the scalar sector ($J^P = 0^+$)



- I=0: $f_0(600)$ or $\sigma(500)$, $f_0(980)$, $f_0(1370)$, $f_0(1500)$, $f_0(1710)$
- I=1/2: $\kappa(800)$, $K_0^*(1430)$
- I=1: $a_0(980)$, $a_0(1450)$

$$L = \prod_{evemts} \left(\sum n_{B_i} P_{B_i} + n_S P_S\right) \qquad P_S = \frac{1}{N_S} g(M)\,\varepsilon(m_{12}^2, m_{13}^2)\,|A|^2$$

$$A = a_0 e^{i\delta_0} A_0 + \sum a_n e^{i\delta_n} A_n(m_{12}^2, m_{13}^2)$$



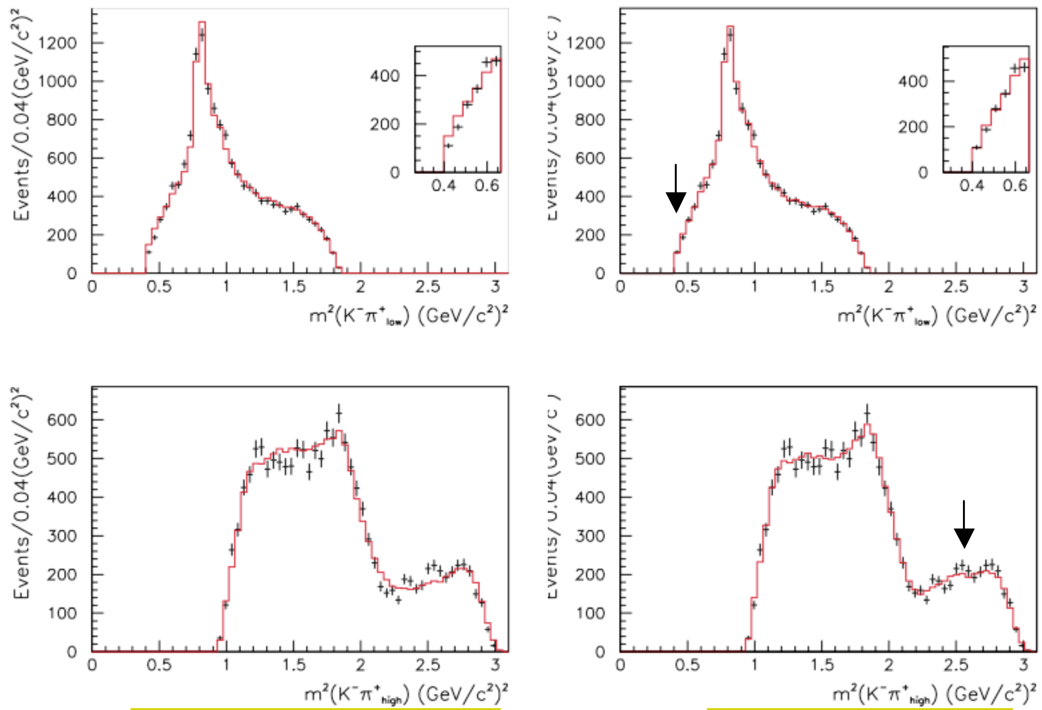
Charm - A Laboratory for Light Quarks

E791 reports
Evidence of
□(800) at
Mass = 797 ± 47 MeV/c²
Width = 410 ± 97 MeV/c²

(Produces better fit of
D^+ □ K□□)

And measures $K_0^*(1430)$
Mass = 1459 ± 9 MeV/c²
(PDG: 1412 ± 6)
Width= 175 ± 17 MeV/c²
(PDG: 294 ± 23)

Also earlier publication on
Evidence for a □(500)



Without □(800) With □(800)

Needs confirmation: FOCUS has □ 5-10 times more data on this

Wu Ning (BES) reports evidence for □(500) in J/□ □ □□⁺□⁻, and □(800) in J/□ □ K*K□
(Hadron Spect. Feb 24-26 2003, Tokyo, Japan)

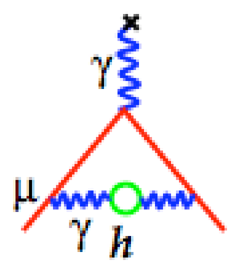
Scalar Mesons and the Muon Anomaly

Muon anomaly $a_\mu = (g-2)/2$ Muon magnetic moment $\vec{\mu}_\mu = \frac{g_\mu e}{2mc}\vec{s}$

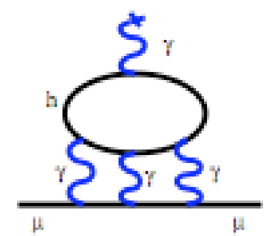
$a_\mu^{exp} - a_\mu^{SM} = (2.7 \pm 1.1) \times 10^{-9}$

$(3.5 \pm 1.1) \times 10^{-9}$ (e^+e^-)
$(1.0 \pm 1.1) \times 10^{-9}$ (τ decays)

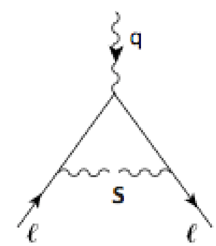
$\sigma(a_\mu^{exp})$	0.8×10^{-9}
$\sigma(a_\mu^{QED})$	0.03×10^{-9}
$\sigma(a_\mu^{EW})$	0.04×10^{-9}
$\sigma(a_\mu^{had,1})$	$0.6–0.7 \times 10^{-9}$
$\sigma(a_\mu^{had,\ LOL})$	$0.3–0.35 \times 10^{-9}$



$a_\mu^{had,1}$



$a_\mu^{had,\ LOL}$



a_μ^{Sll}

Evaluation of contributions from scalar mesons
Narison (‘03, hep-ph/0303004):

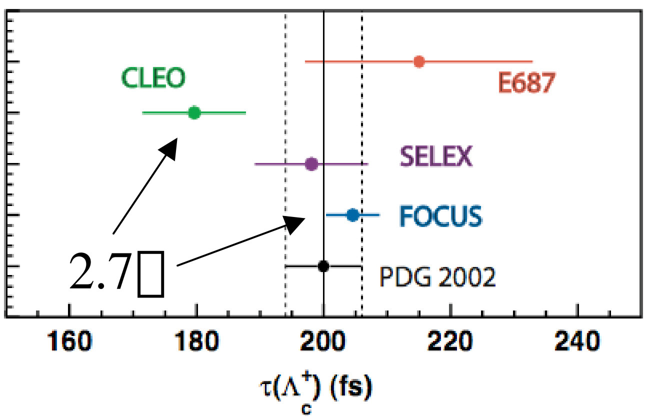
$a_\mu^{S\ had,1}$	$0.03–1.3 \times 10^{-9}$
a_μ^{Sll}	$0–1.1 \times 10^{-9}$

Uncertainty caused by uncertainty on widths of scalar mesons

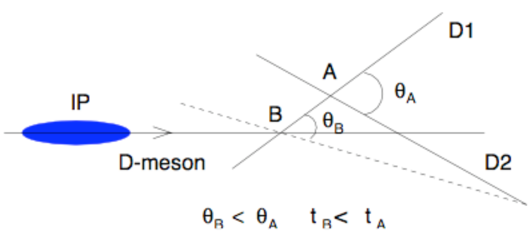
Also Dalitz analysis is an
Important technique to understand

Charm - Precision Vertexing

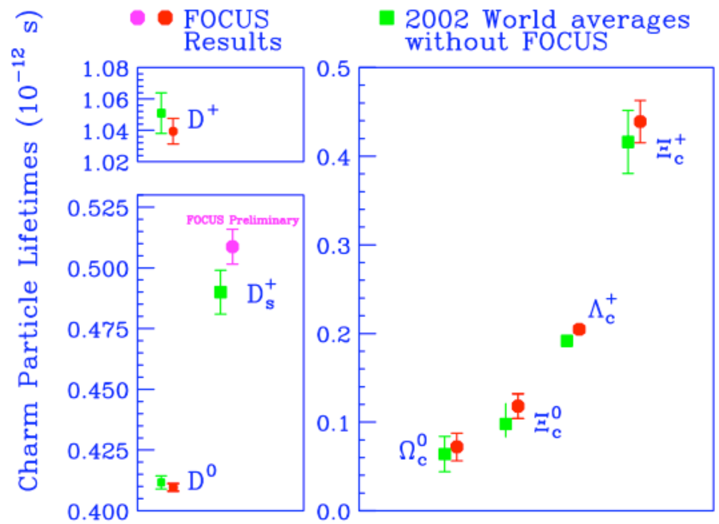
Leading B-physics in vertexing

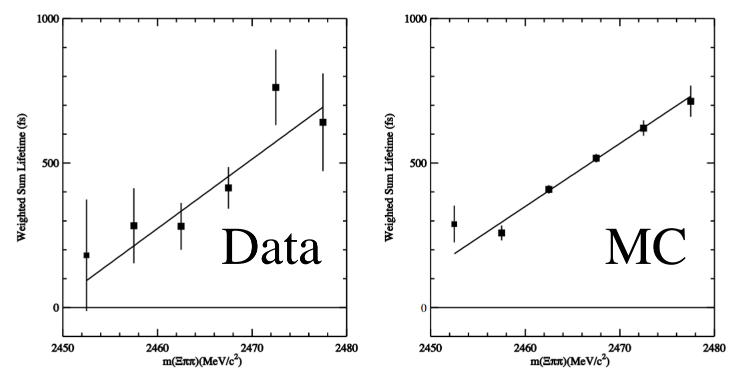


Indications that systematics must be understood for all CP/mixing studies



e.g. CLEO: [illegible] Lifetime



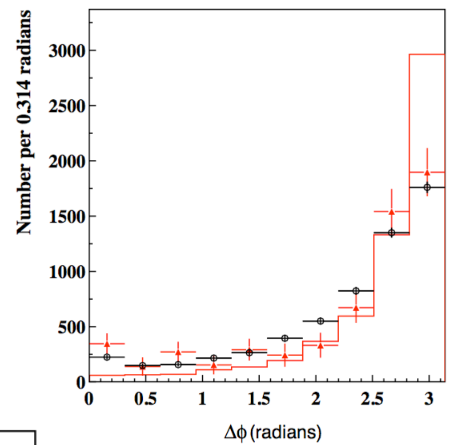


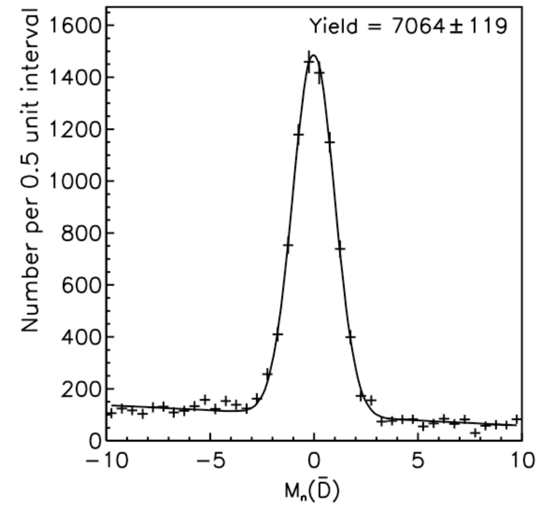
Reconstructed mass

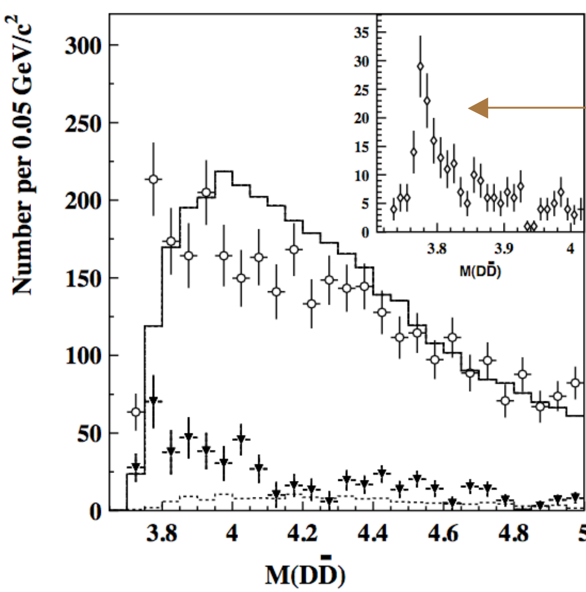
Charm - Room for Surprises

FOCUS has 7000 fully Reconstructed D-Dbars
325 previously (E687)

Compared to Pythia5.6
Pythia used everywhere

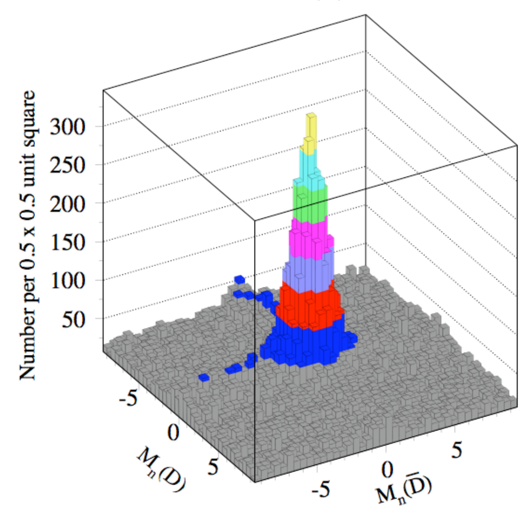






ψ(3770)?

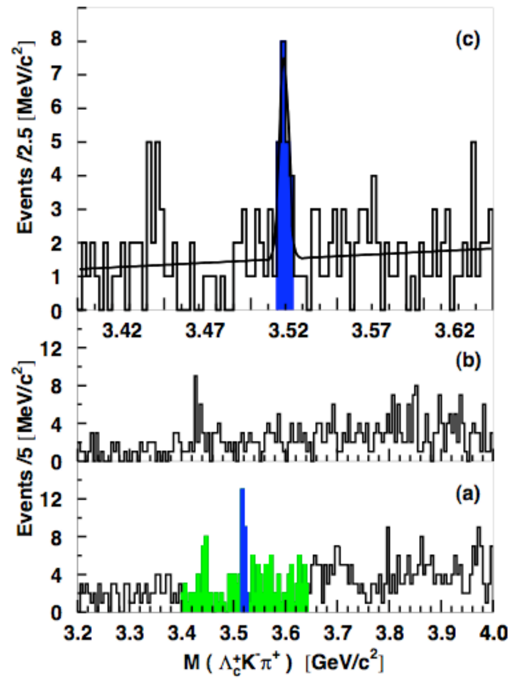
Events with only D-Dbar shows possible "diffractive charm"

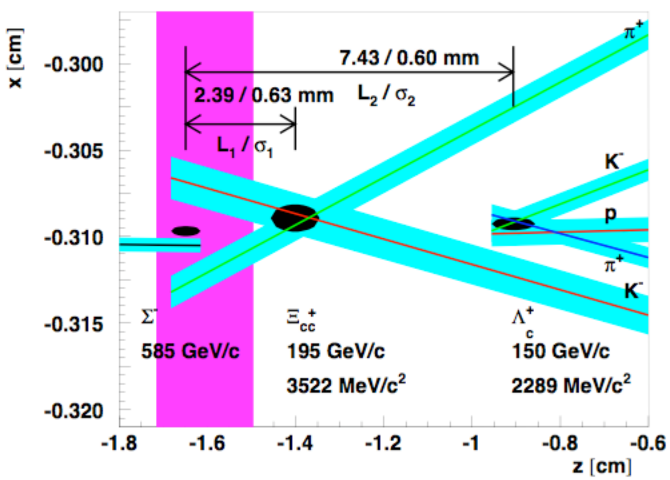


Charm - Room for Surprises

SELEX reported observation of $\Xi_{cc}^{+} \to \Lambda_c^{+} K^{-} \pi^{+}$

with 15.9 events and 6.1 ± 0.5 bkgd
(reported as 6.3σ and 1 $\times$ 10^{-6} prob.)
Mass = 3519 ± 1 MeV/c^2
Lifetime < 33 fs (90% CL)



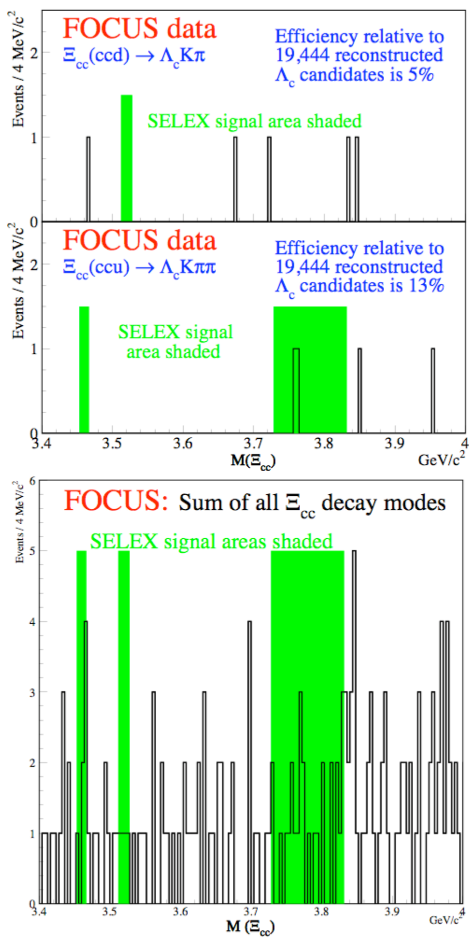


- Almost all Ξ_{cc} from Σ^{-} beam!
- 20% of Λ_c comes from Ξ_{cc} !
  (from sample of 1630 Λ_c's)

What is the production mechanism?

Charm - Room for Surprises

FOCUS does not see $\Xi_{cc}^{+} \to \Lambda_{c}^{+} K^{-} \pi^{+}$ from sample of 20,000 Λ_c's



	$\Xi_{cc}^{+} \to \Lambda_{c}^{+} K^{-} \pi^{+}$	
Experiment	FOCUS	SELEX
Ξ_{cc} Events	< 2.21 @ 90%CL	15.9
Reconstructed Λ_c	19444 ± 262	1630
Relative Efficiency	5%	11%
Ξ_{cc}/Λ_c	<0.23% @ 90%CL	8.9%
SELEX Rel Ξ_{cc} Prod / FOCUS Λ_c	> 39 @ 90%CL	

FOCUS also searched in 20 other decay modes for Ξ_{cc}^{+} and Ξ_{cc}^{++} and do not observe any Ξ_{cc}

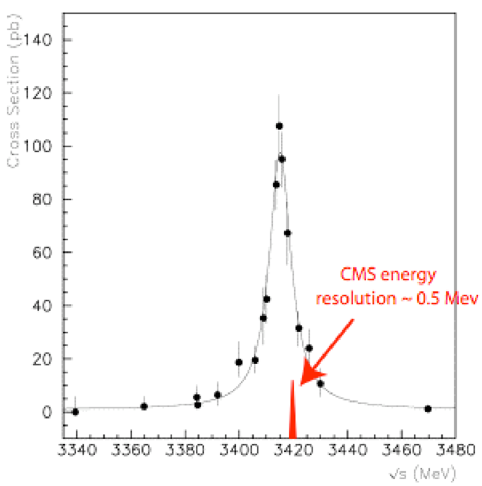
Could this be indicating a strange production mechanism?

E835 - Precision in pbar-p

Measures charmonium states in the pbar accumulator

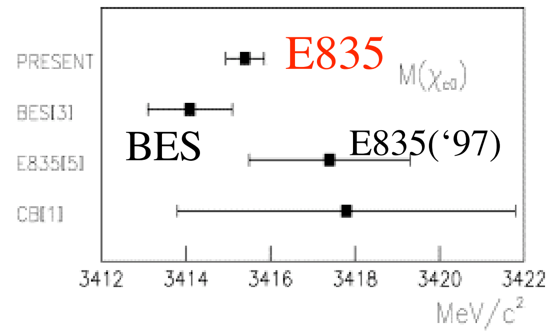
- Very fine energy/mass resolution
- Can produce any spin-parity states directly

New publication on χ_{c0} "10× times data"
plus improvement in pbar lattice

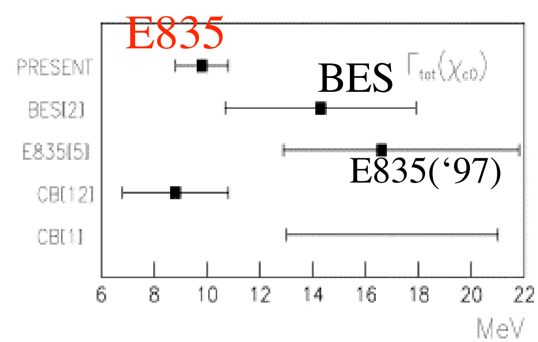


Presents a challenge
to Lattice QCD

χ_{c0} Mass



χ_{c0} Width



Summary

From the report of the recent Fixed Target Analysis Review

(Avi Yagil-CDF(Chair), Steve Brice-MiniBooNE, Bogdan Dobrescu-Theory, Doug Glenzinski-CDF, Wyatt Merrit-D0):

> “The committee was unanimously impressed with the physics output of fixed target experiments at Fermilab. These collaborations have produced and continue to produce world-class results of fundamental importance to High Energy Physics.”

> “The Fixed Target program at Fermilab is broad, deep and extremely productive…many of these datasets are unique and will not be superseded in the foreseeable future.”

Summary II

We should make sure these collaborations receive enough support to finish all the critical measurements, including but not limited to e.g.

- □□/□ from KTeV from the full data set
- CP violation analysis from the full HyperCP data set
- Resolving the NuTeV □/□-bar discrepancy with the SM

However we should not forget that some results can turn out to be more important than what one might at first expect, e.g. scalar mesons. We ask for support in preserving the data and analysis legacy (e.g. via addition of new collaborators) to continue to reap these goldmines. For example FOCUS has 27 publications and 12 PhDs so far and expects additional 30-40 more publications and 14 more PhDs.

Improved experimental techniques and specialized accelerator facilities or beams are necessary to reach the precisions and scope to look for “New Physics”

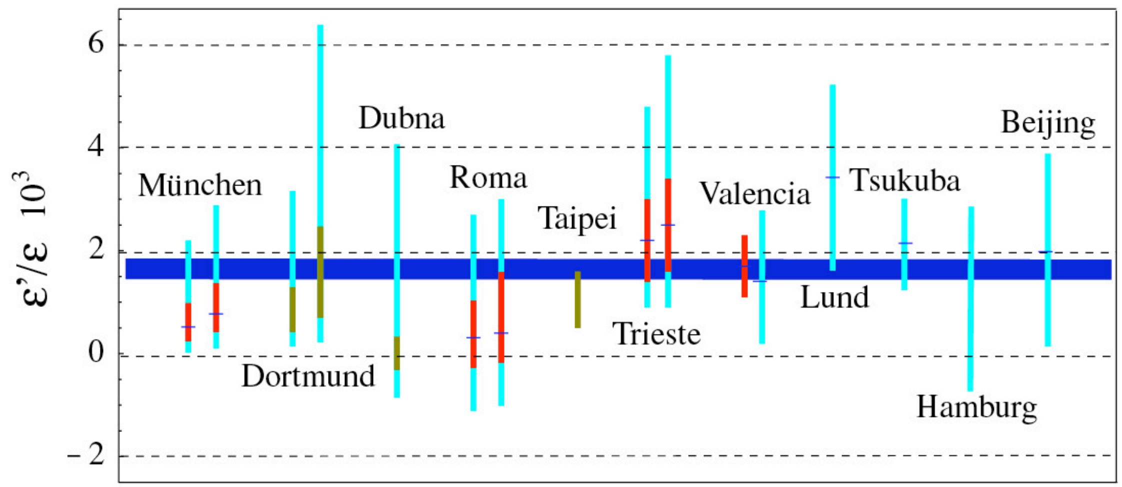
Proceed to Backup Slides

How HEP Publications on slide 2 are counted

- Produced by Jeff Appel and Peter Cooper since 1990
- Hand scanned 5 referred journals: PRL, PRD, Phy. Lett. B, Nucl. Phys. B, and Zeit. fur Physik (later Eur. Phys. J.)
- Individual physicists decided which HEP papers to include, (experimental HEP results from US experiments - usually very relatively few ambiguous papers.)
- Hand scans augmented by SPIRES search
- No attempt to be comprehensive, ignored non-US accelerators with or without US participation, non-accelerator experiments, theory, phenomenology, astrophysics and accelerator physics
- Initiated by Jeff and Peter and carried out each year by them and other members of the Fermilab scientific staff

Theory - "Relating ε'/ε with CKM □"

Taken from recent talk from Ed. Blucher:



Bertolini, Sozzi

Some optimism next round of lattice efforts could reach ±10% level.

Two recent lattice calculations (with similar approximations) find small, negative values for ε'/ε:

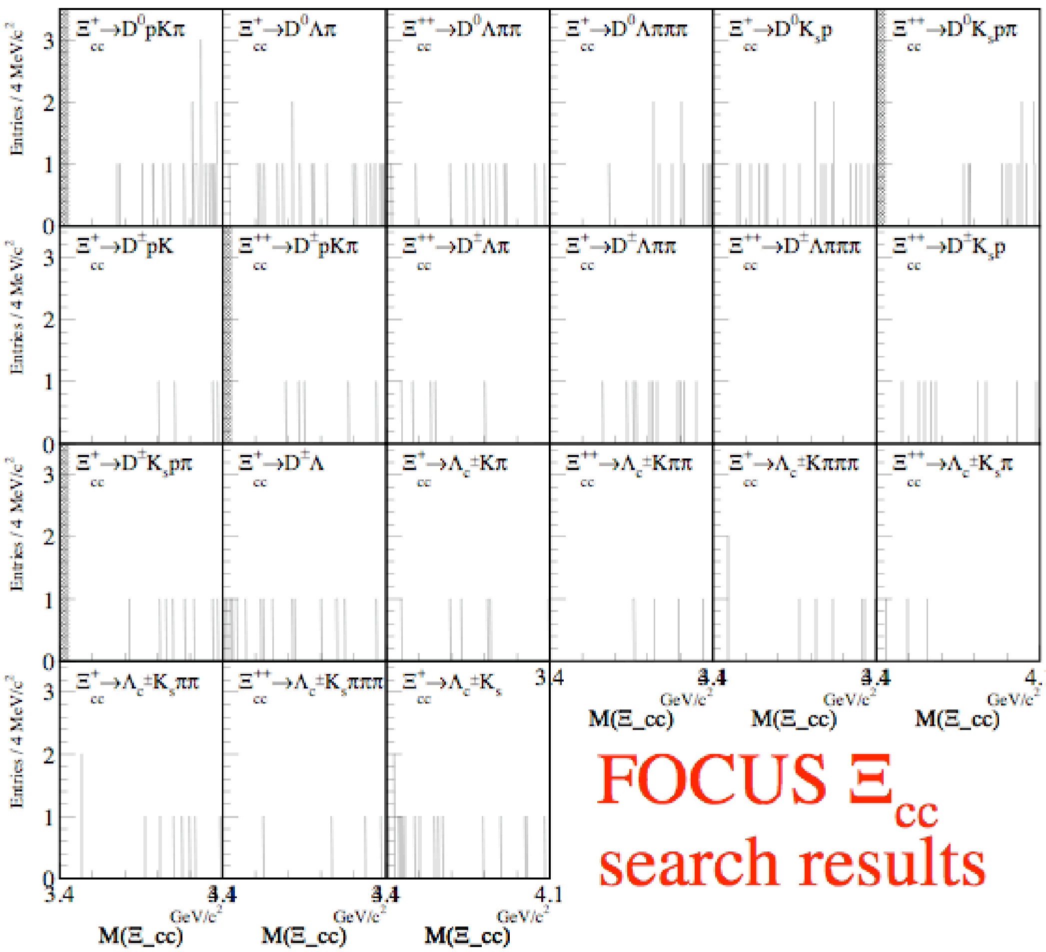
$\mathrm{Re}(\varepsilon'/\varepsilon)=(-4.0\pm2.3)\times10^{-4}$ (RBC Collabor., stat. error only!)

References for Scalar Mesons and Muon g-2

- E791 publication referred to is PRL 89, 2002, 121801
- BES data on □(500) and □(800) presented by Ning Wu at the Int. Symp. on Hadron Spectroscopy, Chiral Symmetry and Relativistic Description of Bound Systems, February 24-26, 2003, Nihon University Kaikan, Ichigaya, Tokyo, Japan
  http://aries.phys.cst.nihon-u.ac.jp/symp03/pdf/Wu.Ning.pdf
- They find masses and widths consistent with E791 but the actual values are model dependent

- Data number on g-2 from C.S.Ozben et al., hep-ex/0211044 v3 (update to PRL 89, 2002, 101804)
- Theory numbers from M.Davier, et al, hep-ph/0208177 v3, and S.Narison, hep-ph/0303004 v1

FOCUS decay modes for Ξ_{cc} Search



FOCUS efficiencies assume Ξ_{cc}^{+} (Ξ_{cc}^{++}) lifetime of 0.2 ps (1.0 ps), a mass of 3.6 GeV/c^2 and production characteristics of a 3.6 GeV/c^2 Λ_c in Pythia. See http://www-focus.fnal.gov/xicc/xicc_focus.html